The Saga of h_c and h_b Search in Heavy Quarkonia

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Abstract

In this brief review, we examine carefully and critically the status of search for the h_c $[\psi(1^1P_1)]$ charmonium state and the h_b $[\Upsilon(1^1P_1)]$ bottonium state, initiated by the E760 experiment. Recent experimental studies at CLEO/BABAR/BELLE are examined in the light of new theoretical and phenomenological understanding.

Keywords: E760 Experiment, charmonium, CLEO/BELLE/BABAR measurements

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1 Introduction

Using a circulating monochromatic antiproton beam at the ISR and a hydrogen gas jet target, experiment R704 studied $p\bar{p}$ interactions at the center of mass energy range of interest for charmonium physics, with unprecedented energy resolution. However, before significant data were taken the ISR was closed down and dismantled. Experiment E760 was resurrected deploying the cooled antiproton beam at Fermilab using much of the same technique as the original CERN experiment. Here much data were accumulated of relevance to charmonium physics in a variety of areas [1,2,3]. We examine in this brief review the E760 result on $h_c[\psi(1^1P_1)]$, the sequel E835 follow up, and recent experimental studies at CLEO/BABAR/BELLE in the light of new theoretical and phenomenological understanding.

2 E760 results on the charmonium $\psi(^1P_1)$

The E760 measurements of $\psi(^1P_1)$ are summarized in Table 1 [3]. These results have attracted theoretical attention [4] with a calculation of the decay width for the $\psi(^1P_1) \to p\bar{p}$ process considering only the constituent quark mass correction, concluding that this kind of correction leads to $\Gamma(^1P_1 \to p\bar{p})$ in the range 1 - 10 eV. This is substantially smaller than an earlier conservative estimate [5] which sensibly normalized the $^1P_1 \to p\bar{p}$ estimate to that of $\eta_c \to p\bar{p}$ decay since both processes violate the helicity selection rule [6] but data is available on the latter process, obtaining 186 eV. We note however that in [4] Murgia's final expression for $\Gamma(^1P_1 \to p\bar{p})$ [c.f. his Eq. (34)], based on constituent quark mass corrections to the usual massless QCD models for exclusive processes, has a multiplicative dependence on $[M(\chi_{c2})/M(\psi(^1P_1)]^{12}$ and hence is very sensitive to (not very well known) mass values for these charmonium states. In E760 [3] there was the incorrect attribution that Kuang-Tuan-Yan [5] predicted $\Gamma(^1P_1 \to J/\psi + \pi^o) \sim 2$ keV. The actual phenomenological approach yields for this rate the value $0.3(\alpha_M/\ \alpha_E)$ keV (c.f. Eq. (35) of [5]) where α_M and α_E are the magnetic and electric couplings in the multipole expansion approach. To maintain theoretical reasonableness (absence of large anomalous magnetic moment for quarks [7]) and the experimental constraint on $\Upsilon(3S) \to \Upsilon(^1P_1)\pi\pi$ from CLEO [8], we must set $\alpha_M = \alpha_E$. Thus $\Gamma(\psi(^1P_1) \to J/\psi + \pi^o) = 0.3$ keV. This is reassuring since it reduces this isospin violating decay which seems too large in E760 [3]. With this value, we infer in the language of E760 [3] that $BR(^1P_1 \to p\bar{p}) \sim 4.33 \times 10^{-4}$ for a total $\Gamma(^1P_1)$ width of say 700 keV suggested by E760 [3], which is then order of magnitude wise quite consistent with $\Gamma(\psi(^1P_1) \to p\bar{p}) = 186$ eV estimated by [5], but at variance with the recent calculation of Murgia [4].

We continue to find the E760 result [3]

$$BR(\psi(^1P_1) \to J/\psi + \pi^o)/BR(\psi(^1P_1) \to J/\psi + \pi\pi) > 5.5(90\% C.L.) \qquad (1)$$

problematic. Isgur et al. [9] estimated that $BR(\psi(^1P_1) \to J/\psi + \pi^o) \sim 10^{-3}$ to 10^{-4}, while Bodwin, Braaten, and Lepage [10] pointed out that the rate for $\psi(^1P_1) \to J/\psi + \pi\pi$ has been estimated within a well-developed phenomenological framework [5] to be of order of 6 keV, leading to $BR(\psi(^1P_1) \to J/\psi + \pi\pi) \sim 10^{-2}$. One of us [11] noted that E760 [3] also did not observe $\psi(^1P_1) \to \gamma\eta_c$, a mode expected to be dominant with a branching fraction $\sim 50\%$ by any reasonable estimate. This could be due to the small $BR(\eta_c \to 2\gamma) \sim 3 \times 10^{-4}$ branching fraction which strains the limits of E760 capacity to detect final state photons from $\eta_c(\to \gamma\gamma)\gamma$. It remains strange that $\psi(^1P_1)$ is discovered via this peculiar isospin violating mode involving single pion emission, while the isospin allowed

dipion mode and the dominant $\gamma\eta_c$ mode remain to be identified. We recognize that a theory based on the stress-energy tensor in QCD can lead to dominance of single pion over dipion emission [12].

The $\psi(^1P_1)$ was confirmed via the same mode in another hadron initiated experiment, E705, [13] at the same mass. However, for increasing the signal-to background ratio, they imposed the cut $M_{\pi\pi} > 80\%$ on the dipion mass distribution inspired by the $M_{\pi\pi}$ distribution in the channel $\psi' \to J/\psi\pi\pi$. Kuang [14] pointed out that this cut is not suitable for $\psi(^1P_1) \to J/\psi\pi\pi$ since the $M_{\pi\pi}$ distribution for this process is not analogous to that in $\psi' \to J/\psi\pi\pi$ but is analogous to the KTY [5] dipion mass distribution for $\Upsilon(3S) \to \Upsilon(^1P_1)\pi\pi$ which is strongly peaked at the low dipion mass region. Therefore the E705 experimental cut actually eliminates 73% of the signal events, so that it eliminates the chance of seeing this dipion decay mode of $\psi(^1P_1)$.

The position for the $\psi(^1P_1)$ charmonium state is expected to be close to the center of gravity (c.o.g) of the ^3P_J states if the spin-spin contribution arising from the Fermi hyperfine interaction (due to one gluon exchange between c and $\bar{c}$) can be neglected [7]. Halzen et al. [15] performed a one-loop perturbative correction to the $^1P_1$-$^3P_{c.o.g.}$ and found it to be $+0.7 \pm 0.2\ MeV$ in accord with E760 [3], thus here the experiment does follow the conventional theoretical expectation.

However, Isgur [16] is surprised by the smallness of the observed splitting, because it is difficult to understand why the non-perturbative couplings of the P-waves to virtual decay channels would not produce relative shifts amongst these states of order 10 MeV. Isgur notes that it would be interesting to understand whether the decoupling from these virtual channels is really as complete as it would appear from the Halzen et al. [15] result (even though the $D^0\bar{D}^{*0}$ continuum at 3871.2 MeV is only a few hundred MeV away) or if this experimental/theoretical degeneracy [3,15] is mainly accidental. We note that Isgur's conjecture [16] of an up to 10 MeV (upward) shift in the position of $\psi(^1P_1)$ is supported by the hyperfine spin-spin correction calculation of Chen and Oakes [17] who find E($^1P_1$) - E($^3P_{c.o.g.}$) = 4 to 6 MeV which is several times larger than the E760 experimental value [3] of 0.93 ± 0.28 MeV. This also suggests that the agreement of the one-loop perturbative calculation [15] with the E760 data is probably fortuitous. It is well to remember that for $\psi(^1P_1)$ with an estimated width < 1.1 MeV, E760 [3] only scanned [in increments (decrements) of 0.5 MeV] around the c.o.g. 3525 MeV of ^3P_J by about 12 MeV (i.e. $3525 \pm 6 MeV$), hence a mass shift of 10 to 6 MeV [16,17] from c.o.g. would have escaped their search! [Note E705 [13] has a 8 MeV/c^2 mass uncertainty in their observation of $^1P_1 \to J/\psi + \pi^o$ which reflects the statistical uncertainty in measuring c.o.g. of χ_{cJ} states. At $\pm 8\ MeV$ E705 is already outside range explored by E760.]

In Table 1 E760 measurements on $\psi(^1P_1)$ are compared with theory.

Table 1: E760 measurements on $\psi(^1P_1)$ are compared with theoretical estimates.

E760 measurement of [3]	Theoretical estimates [9,10,5]
$\Gamma(\psi(^1P_1) \to J/\psi + \pi^0)/\Gamma(\psi(^1P_1) \to J/\psi + \pi\pi)$	1/10 to 1/100
	an earlier [12] much larger
> 5.5 [90% C.L.]	estimate discussed in text
E760 measurement [3]	Theoretical estimate [16,17]
$\Delta M = M(\psi(^1P_1)) - M_{c.o.g.}(\chi_{cJ})$	≥ 4 to 10 MeV
	One loop perturbation [15]
0.93 $\pm$0.28 MeV	0.7 $\pm$ 0.2 MeV

It has been noted [18] that vector confinement would be strongly ruled out by the discovery of the $^1P_1$ h_c spin-singlet $c\bar{c}$ charmonium state by the E760 Collaboration [3]; with typical $c\ \bar{c}$ potential model parameters, the vector confinement spin-spin term predicts a splitting between the c.o.g. of the (χ_{cJ}) ^3P_J triplet states and the h_c $^1P_1$ of order 30 MeV, whereas E760 [3] finds that the splitting is about 1 MeV. Scalar confinement on the other hand would give a very small $h_c -^3 P_{c.o.g.}$ splitting, because there is no scalar spin-spin interaction, and the non relativistic OGE spin-spin interaction is a contact term. Indeed the **L.S.** pattern of the χ states looks like scalar confinement more than vector, independent of the location of the h_c. So the proposed 6-10 MeV shift [16,17] of h_c from $^3P_{c.o.g.}$ would raise the very interesting issues of both modification of the naive $c\bar{c}$ spectrum and the relative proportion of vector vs. scalar components of the confinement potential. We remind that the shift is upward from the c.o.g. value because of the (non relativistic) Stubbe and Martin theorem [19].

Since 1998 there has been a recent paper by Qiao and Yuan [20] which states that the statistical significance of the E760 $\psi(^1P_1)$ [3] is only a slightly more than 3σ signal with no other experiments confirming it (the E705 [13] confirmation is now in doubt as discussed in this section). Hence the existence of $\psi(^1P_1)$ is still based on very weak experimental signals. The authors [20] proposed innovative methods of finding $\psi(^1P_1)$ at HERA-B. However a search strategy at HERA need not be based on E760's $\psi(^1P_1) \to J/\psi + \pi^0$ "discovery" mode, as discussed in the present section. Finally there is the E835 upgrade of the E760 experiment. The design of the E835 detector is basically the same [21] detector as E760 (emphasizing photon detection), but with improvements in tracking and data acquisition capability. With significantly higher statistics the succeeding E835 experiment was unable to confirm E760's enhancement in

$p+\bar{p} \to J/\psi + \pi^0$ at $\sqrt{s}$ = 3526.2 MeV which was supposed to be a candidate for $h_c(^1P_1)$ [22].

3 Study of h_c at BELLE/BABAR

A promising approach for the detection of the h_c has recently been proposed by Suzuki and Gu [23]. Suzuki suggests looking for the h_c by measuring the final state $\gamma\eta_c$ of the cascade $B \to h_c K/K^* \to \gamma\eta_c K/K^*$. This channel is especially timely given the announcement by the BELLE Collaboration of the $\eta_c(2S)$ in B-decays [24] and, previously, the observation of the related decay, $B \to \chi_{c0}K$. [25] That the factorization-forbidden decay $B \to \chi_{c0}K$ occurs as vigorously as the factorization-allowed decays to other charmonia e.g. $B \to \chi_{c1}K$. [25] On the basis of this finding, we expect that another factorization-forbidden decay $B \to h_c K$ may occur just as abundantly as $B \to \chi_{c0}K$. Since $h_c \to \gamma\eta_c$ is one of the two main decay modes of h_c, the decay $B \to h_c K$ cascades down to the final state $\gamma\eta_c K$ about half the time. The only background for this process at the B factories will be the process $B \to \psi' K \to \gamma\eta_c K$. Since the branching fraction for $\psi' \to \gamma\eta_c$ is miniscule, this background is two orders of magnitude smaller than the signal. If one can reconstruct η_c from $K\bar{K}\pi$ or by $\eta\pi\pi$ with say 50% efficiency, 10^7 B's translate to roughly 100 events of the signal. Therefore in principle, we have a very good chance to observe h_c through $B \to \gamma\eta_c K$. For $B(B \to h_c K) \sim B(B \to \chi_0 K$, Suzuki [23] estimated the cascade branching fraction

$$B(B^+ \to h_c K^+ \to \gamma\eta_c K^+ \to \gamma(K\bar{K}\pi)K^+) \sim 2 \times 10^{-5} \tag{2}$$

Gu's estimate [23] of the cascade branching fraction is

$$\begin{aligned} B(B^+ \to h_c K^+ &\to \gamma\eta_c K^+ \\ &\to \gamma(K_S^0 K^+\pi^- + c.c.)K^+ \\ &\to \gamma(\pi^+\pi^- K^+\pi^- + c.c.)K^+) \simeq 3.5 \times 10^{-6} \end{aligned} \tag{3}$$

With 10^8 B's, and an efficiency $\epsilon = 10\%$ [26], there will be about 35 events of the h_c.

The largest (and the only) uncertainty [27] appears to be in the $B \to h_c K/K^*$ branching ratio. The heuristic assumption of a sizable branching for $B \to h_c K/K^*$ was based on the experimental discovery of $B \to \chi_{c0}K$ by BELLE/BABAR. [25] The main difference between χ_{cJ} (J=0,1,2) and h_c is not spins but charge parity. C=+ for χ_{cJ} seem copiously produced, but $C = -$ for h_c is not yet seen. It is difficult to know how this difference in C plays out in the dynamics of decay, and theorists have no reliable way to compute it (if

they are careful and honest). It is nevertheless of interest that theoretical work [28] obtain for the B^- chain of Eq. (2) a value $(4-26)\times 10^{-6}$ where the upper end is actually consistent with Suzuki's estimate. As stated in Suzuki [23], one will have to work harder for precision of the h_c mass, meaning the resolution of the h_c mass. Just identifying h_c at the B factories should not be difficult if it is there. We note also the phenomenological work of Eichten *et al.* [29] on $B \to Kh_c \to K\gamma(500\ MeV)\eta_c$ that they estimate 11.7 K events for this chain. For comparison they noted that the sample that yielded the 39 ± 11 η_c' discovery events by BELLE [25] was (encouragingly) about 30 K events.

Eichten *et al.* [29] estimate that for inclusive $B(B \to h_c X) \sim\ 0.132 \pm 0.06\%$, while Beneke *et al.* [30] predicted that for inclusive $B(B^- \to h_c X) \sim 0.13-0.34\%$ with production of $c\bar{c}$ pair in the color octet state. However it was pointed out by De Fazio [28] that with their estimate of $B(B^- \to K^- h_c) = (2-12)\times 10^{-4}$ and Suzuki's estimate given by Eq. (2), the exclusive mode represents already a sizeable fraction of the inclusive $B^- \to Xh_c$ decay. Hence it will make sense to look for the inclusive $B \to h_c X$ production at BELLE/BABAR if exclusive $B \to h_c K/K^*$ is significantly lower than the Suzuki [23] and De Fazio [28] estimates.

It has been pointed out [31] that the radiative width for $\eta_{c2}(1^1D_2) \to h_c\gamma$ is about 340 keV, while that for $h_c \to \eta_c\gamma$ is about 350 - 500 keV. There are **no radial nodes**, so these should be fairly reliable predictions. So, it looks like both $E1$ modes will be LARGE branching fractions, since the total widths for η_{c2} and h_c are expected to be of 1 MeV scale. It would be a funny way to find the h_c, once we find the η_{c2} experimentally!

There is a potential candidate for η_{c2} at $X(3872)$, [32] which is indeed not far from the nonrelativistic $c\bar{c}$ potential model prediction for $\eta_{c2}(^1D_2)$ at 3799 MeV. [33] An useful test[34] for $X = \eta_{c2}(2^{-+})$ is that the $\eta_{c2} \to \pi^+\pi^-\eta_c$ and γh_c decays are allowed and expected to have widths in the range of 100's of keV,[35] and much larger than that for the isospin violating $\pi^+\pi^- J/\psi$ mode. If the $X(3872)$ were η_{c2}, the total exclusive branching fraction for $B^+ \to K^+\eta_{c2}$ decay, which is non-factorizable and suppressed by an $L = 2$ barrier, would be anomalously large, typically[36] $B(B^+ \to K^+\eta_{c2}) \gg 1.3\times 10^{-3}$. Direct search for $X(3982) \to \pi^+\pi^-\eta_c$ is currently underway at BELLE.[36] From the viewpoint of h_c search, this surpasses a search for $X(3872) \to \pi^0\pi^0 J/\psi$,[35,37] where absence of this mode would imply C=(+) with $c\bar{c}$ candidates in η_c'', χ_{c1}' as well as η_{c2} (it could be consistent also with the deuson model [38] with $J^{PC} = 0^{-+}, 1^{++}$ which remains viable particularly as $X(3872)$ sits on the $D\bar{D}^*$ threshold). Steve Olsen [36] has pointed out that $X(3872) \to \pi^0\pi^0 J/\psi$ is damned hard experimentally! Moreover, the signal, if it is there, is only half of $\pi^+\pi^- J/\psi$; the π^0 efficiency is smaller than that for charged π and the resolution is much much

worse. Hence it will be quite a while before any useful result from $\pi^0\pi^0 J/\psi$ emerges from BELLE/BABAR. Again we note that Eichten *et al.* [29] say that $B \to K\eta_{c2} \to K\gamma(280MeV)h_c \to K\gamma(280MeV)\gamma(500MeV)\eta_c$, 8.1 K events arise (remember again that the sample that yielded the 39 ± 11 η_c' discovery events [24] was about 30 K events), hence they hold out for simultaneous observation of η_{c2} and h_c. We note that the BABAR collaboration [32] in setting an upper limit for the narrow ($\Gamma \leq 1MeV$) h_c state in the decay $B^- \to h_c K^-$, and $h_c \to J/\psi\pi^+\pi^-$, did not deploy $h_c \to \gamma\eta_c$ (with branching ratio $\geq 50\%$), whereas $h_c \to J/\psi\pi^+\pi^-$ including $m_\pi \neq 0$ corrections discussed by one of us [8] is estimated to have miniscule partial width $\Gamma(h_c \to J/\psi\pi^+\pi^-) \sim 1.07$ keV. However, we believe the BABAR collaboration [32] is primarily interested in $X(3872) \to J/\psi\pi^+\pi^-$ decay measurements.

Since the predicted radiative partial width for $h_c \to \gamma\eta_c$ is especially large, which suggests that decays to $\gamma\eta_c$ may provide a discovery channel for the elusive h_c. One possibility [33] is $\gamma\gamma \to \eta_c'$, followed by the decay chain $\eta_c' \to \gamma h_c$, $h_c \to \gamma\eta_c$. Since these electromagnetic couplings are all reasonably well understood, detection of h_c would simply be a matter of accumulating adequate statistics at a high- energy e^+e^- facility (e.g. BELLE/BABAR) or even at RHIC, with sufficient $\gamma\gamma$ luminosity at $\sqrt{s} = 3.7$ GeV. Indeed CLEO, [39] before being reconstructed to become a lower energy e^+e^- facility CLEO-c, had established $\gamma\gamma \to \eta_c'$ and using the method of Barnes *et al.*, [40] concluded that $\Gamma_{\gamma\gamma}(\eta_c') = 1.3 \pm 0.6$ keV. This is at most a factor of 3 lower than quark model estimate [41] with $\Gamma_{\gamma\gamma}(\eta_c') = 3.7$ keV. Munz [42] summarized/obtained other predictions between a factor of 2 to 3 smaller than the quark model estimate. [41]

4 Study of h_b at CLEO

The data set consists of 5.8×10^6 $\Upsilon(3S)$ decays observed with the CLEO III detector at the Cornell Electron Storage Ring (CESR). [43] Hence the CLEO sample of hadronic $\Upsilon(3S)$ decays ($\sim 3.5 \times 10^6$) will be nearly 15 times [44] their previous total some ten years ago. The most straightforward search for h_b was proposed [5] as $\Upsilon(3S) \to \pi^+\pi^- h_b$, where the mass of $h_b \geq 9900 \pm 0.17$ MeV c.o.g. value of ^3P_J mass values according to the Stubbe-Martin theorem. [19] The standard multipole model [5] predicts for $\Upsilon(3S) \to \pi^+\pi^- h_b$ a spectrum in which the $\pi\pi$ mass distribution is strongly peaked at the lower $M_{\pi\pi}$ end. As pointed out by Rosner [45] this comes from the fact that the $\pi\pi$ system should be $J^P = 0^+$, and the $1^- \to 0^+1^+$ transition must proceed with final state L=1 between the dipion and the h_b state. The peaking peculiar to this transition, may allow one to **strengthen the h_b signal by selecting dipions with particularly low mass**. In the case of the earlier CLEO work of F. Butler *et al.* , [8], an upper

limit of $B(\Upsilon(3S) \to \pi^+\pi^- h_b < 0.18\%$ at 90% confidence level was established. The standard multipole model estimate given by one of us[8] is that $B(\Upsilon(3S) \to \pi^+\pi^- h_b)$ should bracket the range 0.022% to 0.08%, while Voloshin [12] will predict a further factor of 0.05 reduction over th standard multipole model value. With nearly 15 times more hadronic $\Upsilon(3S)$ accumulated since ten years ago, it will be interesting to push the $B(\Upsilon(3S) \to \pi^+\pi^- h_b)$ limit further, but deploying the Rosner [45] suggestion of selecting dipions with particularly low mass, to enhance a possible h_b signal. A *caveat* is appropriate when dealing with radial excitation states like $\Upsilon(3S)$ and $\psi(2S)(\psi')$. Rosner [46] pointed out that suppression of $\rho\pi$, $K^*\bar{K}$ decays in the famous $\rho - \pi$ puzzle, could be due to a radial node in $\psi(2S)$. Could there be a similar suppression in say $\Upsilon(3S) \to h_b\pi^+\pi^-$ or $\psi(2S) \to h_c\pi^0$ recently proposed by Kuang [47] as a search method for h_c? Of course $\psi(2S) \to J/\psi\pi\pi$ and $\Upsilon(3S) \to \Upsilon(1S)\pi\pi$ do exist, but are they to be regarded as large or small in some context, let alone that h_c and h_b represent different exclusive channels from radially excited ψ and Υ to J/ψ and $\Upsilon(1S)$ respectively? The calculation of Ackleh and Barnes [41] suggests that radially excited $\eta_c(2S) \to \gamma\gamma$ is at most a factor of three higher than experimental measurement,[39] so here radial node suppression is relatively modest. With respect to $\psi' \to h_c\pi^0$ there could be lack of phase space (not always a problem though since $\psi(4040) \to D^*\bar{D}^*$ is dominant with essentially no phase space [33]) and isospin violation as well (not a problem for Voloshin [12] though). However at BES II, the accumulation of $\psi(2S)$ is only about 1.4×10^7 events, [48] hence Kuang's estimate [47] of $\psi' \to h_c\pi^0$ based on $3 \times 10^7 \psi'$ (and an efficiency $\epsilon = 10\%$) needed to be reduced accordingly.

There could be an indirect test of the validity of the standard multipole Kuang-Yan model [49] outside of h_c and h_b, in terms of their prediction that $\Upsilon(1D) \to \Upsilon(1S)\pi\pi$ is about 24 keV. Here the CLEO experiment [43] obtained for $B(\Upsilon(3S) \to \gamma\gamma\Upsilon(1D))B(\Upsilon(1D_J) \to \pi^+\pi^-\Upsilon(1S)) < 2.7 \times 10^-4$ for a sum over all different J_{1D} values. This upper limit is inconsistent (lower by a factor of about 7) with the rate estimated by Rosner[50] using the Kuang-Yan model for $\Gamma(\Upsilon(1D) \to \pi^+ pi^-\Upsilon(1S))$, [49] and a factor of about 3 higher than the predicted rate based on the model by Ko. [51] The CLEO upper limit [43] is about 30 times higher than those predicted by Moxhay's model [52] which uses the Voloshin [12] approach. There is then the BES measurement [53] of the $\psi'' \to J/\psi\pi\pi$ rate (supportive of Kuang-Yan [49]). Godfrey [54] pointed out that the reduced rate for the $c\bar{b}$ system found by rescaling the BES measurement, [53] is considerably larger than the rate found by rescaling the $\Upsilon(1D) \to \Upsilon(1S)\pi\pi$ CLEO limit. [43] However Godfrey [54] still believes that it is likely one can reconcile the $b\bar{b}$ and $c\bar{c}$ results by properly taking into account $2^3S_1 - 1^3D_1$ mixing.

It is believed that the $\Upsilon(1D)$ found by CLEO at 10,161 MeV [43] is likely

the $\Upsilon(1^3D_2)$ since there is good agreement with lattice QCD calculations and potential models. As stressed by Rosner,[44] since the $B\bar{B}$ threshold is quite far from $\Upsilon(1D)$, coupled channel effects should be small, so the potential models should be reliable. The prediction is probably good to within 0.02 GeV, with 10.16 GeV the central value. Hence we expect the $\Upsilon(1^1D_2)$ to lie in this neighborhood. Production of $\Upsilon(1^1D_2)$ could again lead to large E1 transitions $\Upsilon(1^1D_2) \to \gamma h_b$ and $h_b \to \gamma\eta_b$, for h_b and η_b search. However production of $\Upsilon(1^1D_2)$ from $\Upsilon(3S)$ is a spin-flip transition. The C-parity allows[44] $\Upsilon(3S) \to \Upsilon(1^1D_2) + \gamma$ but it is a highly hindered M1 transition,[55] and is estimated to have a partial width of 0.04 eV!

5 Concluding Remarks

The short term objective on the search for h_c should clearly be concentrated on pushing further the limits on $B \to h_c K/K^* \to \gamma\eta_c K/K^*$ of the Suzuki-Gu[23] approach at BELLE/BABAR. However Eq. (2) and Eq. (3) may represent only the optimistic end of branching ratio expectations. Inclusive $B \to h_c X$ could also be considered. **If** $X(3872) = \eta_{c2}(1^1D_2)$, then $X(3872) \to h_c\gamma \to \eta_c\gamma\gamma$[31] would be a short cut towards h_c discovery, because of the large E1 branching ratios of each leg. An intermediate term objective would be to use the CLEO III 5.8×10^6 $\Upsilon(3S)$ to push lower the limit on $\Upsilon(3S) \to \pi^+\pi^- h_b$ with $h_b \to \gamma\eta_b$, though we understand[44] there are background issues. Development of methods to identify the $1^1D_2(2^{-+})$ states of charmonium [if not X(3872)] and bottonium are a priority, since we wish to deploy the $^1D_2 \to h_{c,b}\gamma \to \eta_{c,b}\gamma\gamma$ favorable search method. A long term objective[33] at BELLE/BABAR (perhaps at RHIC) is to accumulate adequate statistics, with sufficient $\gamma\gamma$ luminosity at $\sqrt{s} = 3.7GeV$, for a search to be conducted on $\gamma\gamma \to \eta_c'$, $\eta_c' \to \gamma h_c$ (with partial width $\sim$ 49 keV), and $h_c \to \gamma\eta_c$ (with partial width $\sim$ 494 keV).

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